

AM CV_N STARS IN THE UCT CCD CV SURVEY

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Abstract High speed photometry of the helium-transferring binary ES Cet – taken over a two-year period (2001 October – 2003 October) – shows a very stable photometric period of 620.211437 ± 0.000038 s, with a tentative indication of curvature in the O–C diagram suggesting a change in period at a rate of $\dot{P} \sim 1.6 \times 10^{-11}$. Phase-resolved spectroscopy of ES Cet obtained with the Hobby-Eberly Telescope shows a clear modulation on the photometric period, the assumed orbital period. We have followed a newly identified AM CVn star (‘2003aw’) photometrically through its 2003 February/March outburst during which it varied in brightness over a range of $V = 16.5 - 20.3$; we find a superhump period of 2041.5 ± 0.3 s. Questions are raised about the reality of the detected spin-up in RX J0806 (Hakala et al. 2003; Strohmayer 2003).

Keywords: techniques: photometric, spectroscopic - binaries: close - stars: individual: ES Cet, 2003aw, cataclysmic variables

Introduction

There are currently ten known unequivocal double degenerate interacting binaries (AM CVn stars), namely ES Cet, AM CVn, HP Lib, CR Boo, KL Dra, V803 Cen, CP Eri, ‘2003aw’, GP Com and CE-315, ranging in orbital period (P_{orb}) from 10.3 – 65.1 min. These stars have proper spectroscopic and photometric credentials – their spectra show helium emission or absorption lines; no hydrogen can be present in these systems. There are two additional candidate AM CVn stars of suspected short orbital period, RX J0806 at $P_{orb} = 5.35$ min (Israel et al. 2002; Ramsay et al. 2002) and V407 Vul (Cropper et al. 1998) at $P_{orb} = 9.49$ min. Their classification as AM CVn stars is, however, not unambiguous; there is some (tentative) evidence for the presence of hydrogen in the spectrum of RX J0806 (Israel et al. 2002), and the spectrum of V407 Vul

is that of a K star (Steeeghs 2003) making it appear like an intermediate polar precursor at quite long orbital period (Warner 2003). In this interpretation, the 9.49-min photometric and X-ray modulation is associated with the spin period of the primary, not the orbital period. Table 1 lists all the AM CVn stars, including the two candidates.

Table 1. The AM CVn stars

<i>Object</i>	<i>V (mag)</i>	<i>P_{orb} (s)</i>	<i>P_{sh} (s)</i>	<i>References</i>
RX J0806	21.1	321.25 ^a		1, 2
V407 Vul	19.9	569.38 ^a		3
ES Cet	16.9	620.21144		4, these proceedings
AM CVn	14.1	1028.7	1051.2	5, 6
HP Lib	13.7	1102.7	1119.0	7, 8
CR Boo	13.0 – 18.0	1471.3	1487	9, 10
KL Dra	16.8 – 20	1500	1530	11
V803 Cen	13.2 – 17.4	1612.0	1618.3	12
CP Eri	16.5 – 19.7	1701.2	1715.9	13
‘2003aw’	16.5 – 20.3		2041.5	14, these proceedings
GP Com	15.7 – 16.0	2974		15, 16
CE-315	17.6	3906		17, 18

^aNot yet definitively established as orbital periods.

¹Israel et al. (2002); ²Ramsay et al. (2002); ³Cropper et al. (1998); ⁴Warner & Woudt (2002); ⁵Solheim et al. (1998); ⁶Skillman et al. (1999); ⁷O’Donoghue et al. (1994); ⁸Patterson et al. (2002); ⁹Wood et al. (1987); ¹⁰Patterson et al. (1997); ¹¹Wood et al. (2002); ¹²Patterson et al. (2000); ¹³Abbott et al. (1992); ¹⁴Woudt & Warner (2003a); ¹⁵Nather et al. (1981); ¹⁶Marsh et al. (1991); ¹⁷Ruiz et al. (2001); ¹⁸Woudt & Warner (2002).

The UCT CCD CV Survey

The UCT CCD CV Survey is a high speed photometric survey of faint cataclysmic variable stars (CVs) using the University of Cape Town (UCT) CCD photometer (O’Donoghue 1995) in frame-transfer mode, in combination with the 1.0-m and 1.9-m reflectors at the Sutherland site of the South African Astronomical Observatory.

ES Cet. Initial high-speed photometry of ES Cet obtained during four nights in 2001 October (Warner & Woudt 2002) showed a clear modulation at 620.26 s – in the Fourier transform only the fundamental and its first three harmonics of the 620.26-s modulation were present. The spectrum of ES Cet (see Fig. 2) is dominated by HeII emission lines, and hence its position amongst the AM CVn stars is secure. From the low mass ratio ($q = 0.094$), and the predicted rate of mass transfer \dot{M} of $\sim 1 \times 10^{-8} M_{\odot} \text{ y}^{-1}$ at $P_{orb} = 620 \text{ s}$ (Warner 1995), one expects

that the photometric modulation originates from superhumps due to tidal distortions in the accretion disc (Patterson et al. 2002). In this case, the orbital period would be a few per cent lower than the observed photometric modulation.

We have followed ES Cet photometrically over the last two years and the photometric modulation is surprisingly stable. If indeed it arises from a superhump modulation, it is the most stable superhump detected to date (Patterson, priv. comm.). The O–C diagram of all the UCT CCD photometry taken between 2001 October and 2003 October is shown in Fig. 1, phased according to the ephemeris given in Eq. 1. Even though there is some scatter in the O–C diagram, there are no substantial phase shifts or period changes (as might have been expected were the modulation due to superhumps).

$$\text{HJD}_{\min} = 245\,2203.3739512 + 0.0071783731(4) E \quad (1)$$

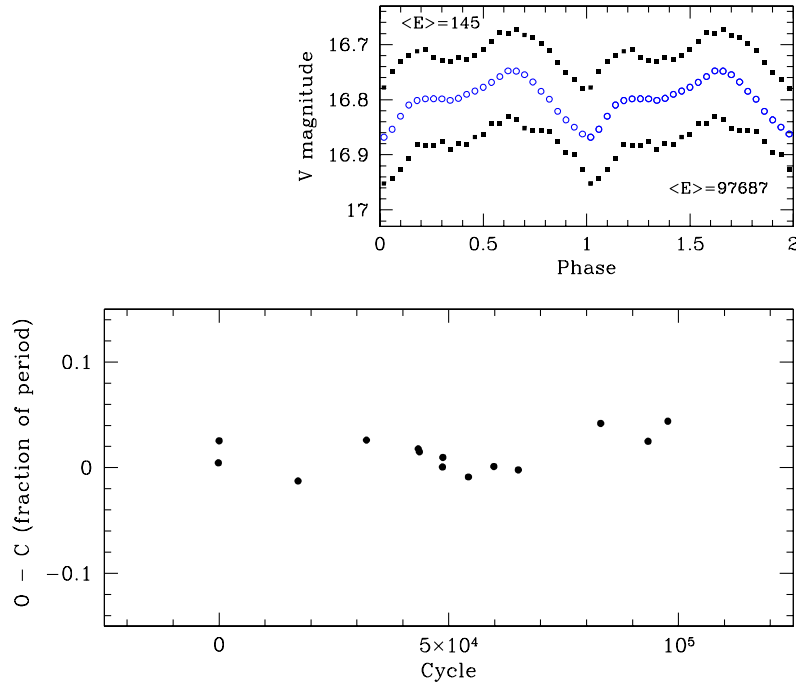


Figure 1. The O–C diagram (lower panel) of all the UCT CCD photometry obtained of ES Cet over the last 2 years. The upper panel shows the average light curve of all the data (open circles) compared with the mean light curve of two individual runs spaced two years apart.

With the two-year baseline, there is a slight hint of upwards curvature in the O–C diagram, which implies a lengthening of the photometric period. If the data are split in two halves ($E \sim 0 - 50\,000$ cycles and $E \sim 50\,000 - 100\,000$ cycles, with an overlap of the dense data coverage at $E \sim 50\,000$ cycles), we find that the period is indeed larger in the second half: P_{orb} (1st year) = $620.211391 (\pm 50)$ s versus P_{orb} (2nd year) = $620.211841 (\pm 96)$ s. The amount of variation is consistent with the curvature seen in the lower panel of Fig. 1. It implies $\dot{P} \sim 1.6 \times 10^{-11}$ – fairly close to the expected rate of change of 6×10^{-12} (Warner & Woudt 2002) for a high \dot{M} system. We realise that the data coverage is still rather small, and another two years of photometry will be required to confirm this trend in the O–C diagram.

Apart from the extended photometric coverage, we have obtained phase-resolved spectroscopy (with a time resolution of 30 s) of ES Cet using the Low Resolution Spectrograph on the Hobby-Eberly Telescope (HET) at the McDonald Observatory in Texas. Two visits of 40 minutes, and a third observing run 30 minutes long, showed very clearly that the spectral lines varied on the photometric period of 620.21 s. This has also been seen by Steeghs (2003) in two consecutive nights of phase-resolved Magellan data. The averaged HET spectra (combining all the spectra of the three different ES Cet observations) is shown in Fig. 2. Fig. 3 shows the variation of the centroid of the He II 4686 Å emission line as a function of the photometric ephemeris given in Eq. 1.

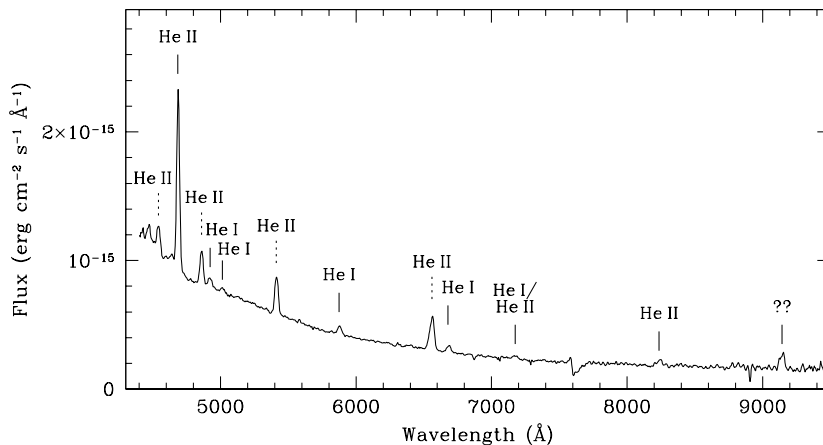


Figure 2. The averaged spectra of ES Cet taken with the Hobby-Eberly telescope.

The spectrum consists mainly of He I and He II emission lines (lines of the He II Pickering series are marked by the dashed vertical bars in Fig. 2); there is one line at $\lambda \sim 9140$ Å which we haven't yet been able

to identify. The strong emission lines are somewhat unexpected for an object of inferred high \dot{M} . The low spectral resolution of the HET spectra fails to show the double-lined nature of the emission lines, but higher resolution spectra (Steehls 2003) clearly show the double emission lines, indicating the presence of an accretion disc. The spectral resolution of the HET spectra is too low for generating Doppler tomograms, cf. Steeghs (2003).

Given the stability of the photometric period and spectroscopy modulation on the photometric period, it seems that the 620-s modulation is more probably the orbital period of the system and not the superhump period as commonly expected for a low-mass ratio, high \dot{M} system.

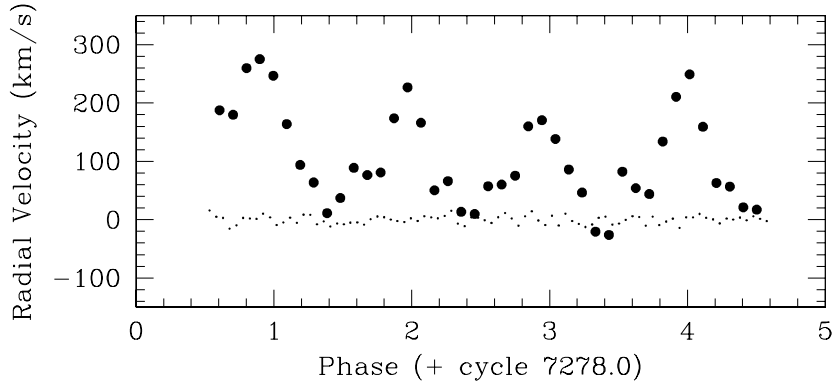


Figure 3. Variations in the centroid of the He II 4686 Å emission line (big dots), phased on the ephemeris given in Eq. 1. The small dots show the [O I] 5577 Å night sky line.

‘2003aw’. Shortly after its outburst in 2003 February, ‘2003aw’ was identified as a candidate supernova in a supernova search (Wood-Vasey et al. 2003), but a spectrum taken by Chornock & Filippenko (2003) revealed weak He I emission lines at zero redshift, making ‘2003aw’ a candidate AM CVn star caught in a high state. Initial photometry with the UCT CCD confirmed this suggestion after finding a photometric modulation in the light curve with a period of 2034 ± 3 s (Woudt & Warner 2003b), with recurring dips in the light curve during the high state – possibly indicating shallow eclipses.

We followed ‘2003aw’ through its decline from the high state into the intermediate state, and during both phases a photometric modulation of identical period was found: $P_{sh} = 2041.5 \pm 0.3$ s (Woudt & Warner 2003a). The dips did not occur during the intermediate state. However,

during the intermediate state we observed a ‘cycling’ in brightness of ≥ 0.4 mag on a time-scale of ~ 16 h. This behaviour is also seen in other AM CVn stars in intermediate states; in CR Boo ($P_{orb} = 1471$ s) the cycle time is ~ 19 h, with a range of 1.1 mag and in V803 Cen ($P_{orb} = 1612$ s) the cycle time is 22 h, with a range of 1.1 mag. ‘2003aw’ has two other interesting aspects:

- The presence of sidebands to the fundamental *superhump* frequency and two of its harmonics during the high state. The frequency separation of these sidebands corresponds roughly to the ‘cycling’ time scale.
- A short lived (~ 1 day) brightening of $\Delta V \sim 1.8$ mag occurred during the high state, resembling the behaviour of some intermediate polars (Schwarz et al. 1988; van Amerongen & van Paradijs 1989).

‘2003aw’ seems to know its place within the emerging hierarchy of AM CVn stars. The systems of shortest orbital periods ($P_{orb} \lesssim 1200$ s) have stable high \dot{M} discs, systems with periods between $\sim 1200 - 2500$ s – to which ‘2003aw’ belongs – have unstable high \dot{M} discs (the equivalent of the nova-likes of VY Scl type), and systems with orbital periods $P_{orb} \gtrsim 2500$ s have low \dot{M} , and are perhaps permanently in a low state.

On the spin-up in RX J0806

Two recent papers (Hakala et al. (2003); Strohmayer (2003)) presented evidence that the orbital period in RX J0806 is undergoing a spin up. Evidence for this was based on three epochs of data: X-ray data taken with ROSAT in 1994-1995 (Burwitz & Reinsch 2001), and two sets of optical data taken with the VLT and NOT (Hakala et al. 2003) in 2001 Nov/2002 Jan, and 2003 Jan/Feb, respectively. Of the two optical data sets, the first data set (2001/2002) suffers from severe aliasing (Hakala et al. 2003), and as a result, the deduced period evolution depends critically on the assumption that the X-ray period in the 1994/1995 ROSAT data set is correct.

The X-ray data (Burwitz & Reinsch 2001) were taken in 1994 October and 1995 April with a total of 13 400 s of integration time. This amounts to the equivalent of 42 cycles of the 5-min modulation spread out over ~ 180 days ($\sim 50\,000$ cycles). With such poor data coverage, it is impossible to determine periods to the accuracy of 0.4 ms as quoted in Burwitz & Reinsch (2001) and perpetuated in Hakala et al. (2003). The aliasing is severe, as shown in Figure 4 of Burwitz & Reinsch (2001), and the highest peak in the forest of aliases is not necessarily the correct

period. Each alias peak can be determined with a precision of 0.4 ms (largely determined by the baseline of the observations), but the choice of alias peak can lead to inaccurate results. To illustrate that, we have selected a few observing runs of ES Cet – mimicking an approximately similar data coverage (80 out of 32 000 cycles) – and show the FT for this small data set next to the complete data set in Fig. 4.

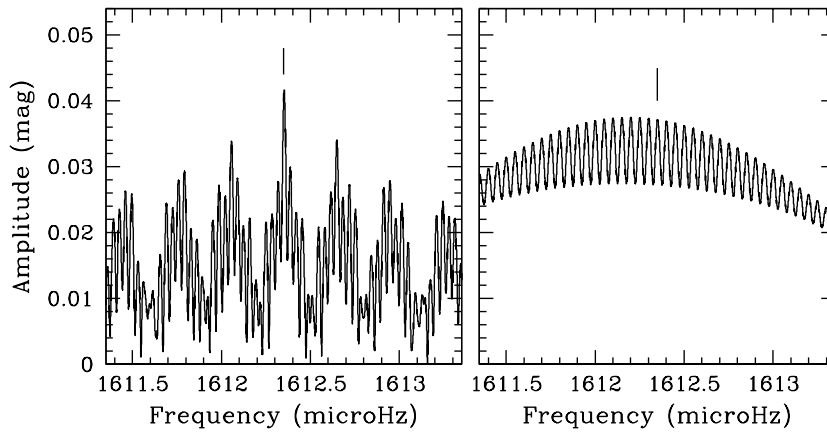


Figure 4. A comparison of the Fourier transform of all the SAAO observations of ES Cet in the period 2001 October – 2003 October (left panel) with a selected subsample with limited data coverage the equivalent of 80 cycles over 32 000 cycles (right panel). The proper photometric period is marked by the vertical bar in both diagrams.

If the nearest alias to the right (see Figure 4 of Burwitz & Reinsch) of the preferred period in Burwitz & Reinsch (2001) is chosen (i.e., a lower period), the entire period evolution disappears (Figure 2 of Hakala et al. 2003). At best, the evidence for a spin-up in RX J0806 is tentative; there are currently insufficient data to claim (with high significance) a period evolution in this object. It remains to be seen if the proposed period evolution in V407 Vul (Strohmayer 2002) suffers from the same problem of poor data coverage (in that case there is X-ray data for 172 cycles spread over 250 000 cycles of the 569-s modulation).

Discussion

To determine the period evolution of short period AM CVn stars a dedicated long-term campaign is needed in order to eliminate aliases and cycle count uncertainties. After two years of observations of ES Cet, the O–C diagram is starting to show a slight upwards curvature (indicating a increase in period) and we derive a (tentative) value for $\dot{P} \sim 1.6 \times 10^{-11}$,

or the equivalent $\dot{\nu} \sim -4 \times 10^{-17} \text{ Hz s}^{-1}$. Insecure though it is, it may be the first detection of a \dot{P} in an AM CVn system.

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References

- Abbott, T.M.C., Robinson, E.L., Hill, G.J., et al. (1992). *ApJ*, 399, 680
- Burwitz, V., Reinsch, K. (2001). In X-ray astronomy: stellar endpoints, AGN, and the diffuse X-ray background, eds. N.E. White, G. Malaguti, G.G.C. Palumbo. AIP Conf. Proc., 599, 522
- Chornock, R., Filippenko, A.V. (2003). *IAUC*, 8084, 3
- Cropper, M., Harrop-Allin, M.K., Mason, K.O., et al. (1998). *MNRAS*, 293, 57L
- Hakala, P., Ramsay, G., Wu, K., et al. (2003). *MNRAS*, 343, 10L
- Israel, G.L., Hummel, W., Covino, S., et al. (2002). *A&A*, 368, 13L
- Marsh, T.R., Horne, K., Rosen, S. (1991). *ApJ*, 366, 535
- Nather, R.E., Robinson, E.L., Stover, R.J. (1981). *ApJ*, 244, 269
- O'Donoghue, D. (1995). *Baltic Astr.*, 4, 519
- O'Donoghue, D., Kilkenney, D., Chen, A., et al. (1994). *MNRAS*, 271, 910
- Patterson, J., Fried, R.E., Rea, R., et al. (2002). *PASP*, 114, 65
- Patterson, J., Kemp, J., Chambrook, A., et al. (1997). *PASP*, 109, 1100
- Patterson, J., Wlaker, S., Kemp, J., et al. (2000). *PASP*, 112, 625
- Ramsay, G., Hakala, P., Cropper, M. (2002). *MNRAS*, 332, 7L
- Ruiz, M.T., Rojo, P.M., Garay, G., Maza, J. (2001). *ApJ*, 552, 679
- Schwarz, H.E., van Amerongen, S., Heemskerk, M.H.M., et al. (1988). *A&A*, 202, 16L
- Skillman, D.R., Patterson, J., Kemp, J., et al. (1999). *PASP*, 111, 1281
- Solheim, J.-E., Provencal, J.L., Bradley, P.A., et al. (1998). *A&A*, 332, 939
- Steeghs, D. (2003). Workshop on Ultracompact Binaries, Santa Barbara.
- See http://online.kitp.ucsb.edu/online/ultra_c03/steeghs/
- Strohmayer, T.E. (2002). *ApJ*, 581, 577
- Strohmayer, T.E. (2003). *ApJ*, 593, 39L
- van Amerongen, S., van Paradijs, J. (1989). *A&A*, 219, 195
- Warner, B. (1995). *Ap&SS*, 225, 249
- Warner, B. (2003). These proceedings
- Warner, B., Woudt, P.A. (2002). *PASP*, 114, 129
- Wood, M.A., Casey, M.J., Garnavich, P.M., et al. (2002). *MNRAS*, 334, 87
- Wood, M.A., Winget, D.E., Nather, R.E., et al. (1987). *ApJ*, 313, 757
- Wood-Vasey, W.M., Aldering, G., Nugent, P., Li, K. (2003). *IAUC*, 8077, 1
- Woudt, P.A., Warner, B. (2002). *MNRAS*, 328, 159
- Woudt, P.A., Warner, B. (2003a). *MNRAS*, in press
- Woudt, P.A., Warner, B. (2003b). *IAUC*, 8085, 3